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Habitability of Planets Orbiting Cool Stars

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Abstract. Terrestrial planets are more likely to be detected if they orbit M dwarfs due to the favorable planet/star size and mass ratios. However, M dwarf habitable zones are significantly closer to the star than the one around our Sun, which leads to different requirements for planetary habitability and its detection. We review 1) the current limits to detection, 2) the role of M dwarf spectral energy distributions on atmospheric chemistry, 3) tidal effects, stressing that tidal locking is not synonymous with synchronous rotation, 4) the role of atmospheric mass loss and propose that some habitable worlds may be the volatile-rich, evaporated cores of giant planets, and 5) the role of planetary rotation and magnetic field generation, emphasizing that slow rotation does not preclude strong magnetic fields and their shielding of the surface from stellar activity. Finally we present preliminary findings of the NASA Astrobiology Institute's workshop "Revisiting the Habitable Zone." We assess the recently-announced planet Gl 581 g and find no obvious barriers to habitability. We conclude that no known phenomenon completely precludes the habitability of terrestrial planets orbiting cool stars.

1. Introduction

Initially dismissed as potential habitats, planets orbiting M dwarfs have lately seen renewed interest (Tarter et al. 2007; Scalo et al. 2007). With lower luminosities, their “habitable zones” (HZ), the range of orbits in which an Earth-like planet could support surface water (Kasting et al. 1993), are significantly closer-in than for solar-type stars. This proximity leads to new perils such as increased susceptibility to stellar activity and stronger tidal effects. The discovery of exoplanets spurred more detailed and careful evaluation of these phenomena, and many researchers now argue that they are not as dangerous for life as previously feared. On the contrary, these planets may be ideal laboratories to test models of geophysics, atmospheric dynamics, celestial mechanics, photochemistry, aeronomy, and ultimately habitability.

Without analogs in our Solar System or adequate remote sensing capabilities, the surface properties of M dwarf planets can only be considered theoretically. Nonetheless, progress has been made in several areas, such as modeling of planetary interiors (Sotin et al. 2007; O’Neill & Lenardic 2007), atmospheric mass loss (Yelle 2004; Segura et al. 2010), atmospheric dynamics (Joshi 2003; Heng & Vogt 2010), and tidal effects (Jackson et al. 2008; Heller et al. 2010). This chapter is a multidisciplinary study of the potential habitability of M star planets, but with an astrophysical bias. A full treatment would require far more space than permitted by this format. For a more comprehensive analysis of M dwarf planet habitability (and habitability in general), see Tarter et al. (2007), Scalo et al. (2007), and § 7.

This chapter is organized as follows. First we examine the current detection limits of terrestrial planets due to stellar variability. Second, we explore the different chemical reactions in planetary atmospheres due to different stellar spectral energy distributions. Next we examine tidal effects. Fourth, we consider the possible existence of “habitable evaporated cores” of giant planets. Fifth, we explore the magnetic fields of terrestrial planets. Finally, we report key interdisciplinary findings from a recent NASA Astrobiology Institute workshop titled “Revisiting the Habitable Zone.”

2. Is M Dwarf Variability a Barrier to Detecting Earth-Mass Planets?

With > 500 extra-solar giant and super-Earth planets detected around nearby stars, we are now probing the dependence on stellar mass of planet formation and migration. At the same time, we are pushing the limits of radial velocity (RV) planet detection methods below “super-Earths” (planet mass $m_p \leq 10 M_\oplus$) and toward a bona fide Earth analog, e.g. Mayor et al. (2009). M dwarfs play a critical role in both of these scientific pursuits. The diminutive masses of M dwarfs result in a higher sensitivity to lower-mass planets at a given RV precision, and many of the lightest exoplanets have been detected around M dwarfs with semi-amplitudes of ~ 1 m/s (Mayor et al. 2009). New instruments have the potential to push the instrumental residuals down to 10 cm/s (Pepe & Lovis 2008), the amplitude of an Earth-mass planet in the habitable zone of a solar-type star. The amplitude of that same planet around an early-type M dwarf is 30-60 cm/s and > 1 m/s for late-M dwarfs. These limits imply that we currently have the instrumental precision necessary to detect terrestrial planets in the HZs of the nearest M dwarfs.

On the other hand, M dwarfs are hundreds of times fainter than G stars at optical wavelengths. As a result, there has been a surge in near-infrared RV survey efforts with

high-resolution spectrographs such as NIRSPEC on Keck and CRIRES on the VLT. Using telluric lines for wavelength calibration, these surveys are capable of reaching RV precisions of 20-100 m/s on M and L dwarfs depending on the rotation rate of the star (Blake et al. 2010). With additional calibration from either an ammonia or methane gas cell, these instruments can reach RV precisions of 5-10 m/s for mid to late M dwarfs (Bean et al. 2010a,b). While the amplitude of the RV signature is larger around these lighter mass stars, M dwarfs suffer from more flaring and starspot activity than their solar-type counterparts. These photospheric activity sources introduce perturbations, often called jitter, into both the photocenter of the star and the disk-averaged radial velocity. The degree of the perturbation depends on the rotation rate of the star, the flare occurrence rate, the starspot lifetime and the degree of starspot coverage. Makarov et al. (2009) used a simple starspot model to estimate that RV jitter for F, G and K stars can reach up to 69, 38 and 23 cm/s, respectively and, thus, inhibit our ability to detect Earth-mass planets in the HZ.

Stellar variability may be measured in several different ways. The ultra-precise photometry from the *Kepler* telescope shows that, in general, early-M dwarfs display less astrophysical jitter than their FGK counterparts (Basri et al. 2010; Ciardi et al. 2010). However, *Kepler* data include few mid-M dwarfs and no late-M dwarfs. Additionally, jitter levels may vary from star to star within the same spectral class suggesting we need to quantify the jitter for individual targets. In fact, in some instances the variability of the $H\alpha$ line, a common proxy for stellar activity, is *anti-correlated* with the RV jitter (Zechmeister et al. 2009).

Starspots are another source of astrophysical noise, and many groups have developed basic (one continuous, circular spot) and complex (various spot lifetimes and temperatures, multiple spots at a range of latitudes) models. The expected contribution to RV jitter from starspots on M dwarfs was addressed by Reiners et al. (2010) using a model with a single spot and multiple wavelengths and stellar rotation rates. For example, a 2800 K star with a 2600 K spot and a 2 km/s rotation rate will have an RV jitter of 10 m/s in the optical and 2 m/s in the infrared. These levels go up to 14 and 10 m/s, respectively, for a rotation rate of 10 km/s. This jitter is larger than the 2 m/s precision needed to detect an Earth-mass planet in the habitable zone of an M6 star.

RV technology will soon reach the 10 cm/s precision necessary to detect Earth-mass planets in the HZs of nearby stars. However, we do not know the levels of intrinsic stellar jitter of stars in our local neighborhood – the majority of which are M dwarfs. Recent advances have demonstrated that broad assumptions based on spectral type are inadequate. Precise photometry and complex star spot modeling, as well as the forthcoming statistical results from the *Kepler*, *MOST* and *CoRoT* missions could provide valuable insight, but, in certain cases, jitter may prevent the detection of terrestrial planets.

3. Implications of M Dwarf Spectral Energy Distributions on Life Detectability

Most plans to search for and characterize life on extrasolar planets involve probing the atmospheric chemistry of those planets by analyzing their spectra to search for specific gaseous components which can only be produced by biological processes. For example, there have been calls to search for the simultaneous presence of methane (CH_4) and either molecular oxygen (O_2), or its photochemical by-product, ozone (O_3) (for a review see Des Marais et al. 2002). Others have suggested looking for life by searching

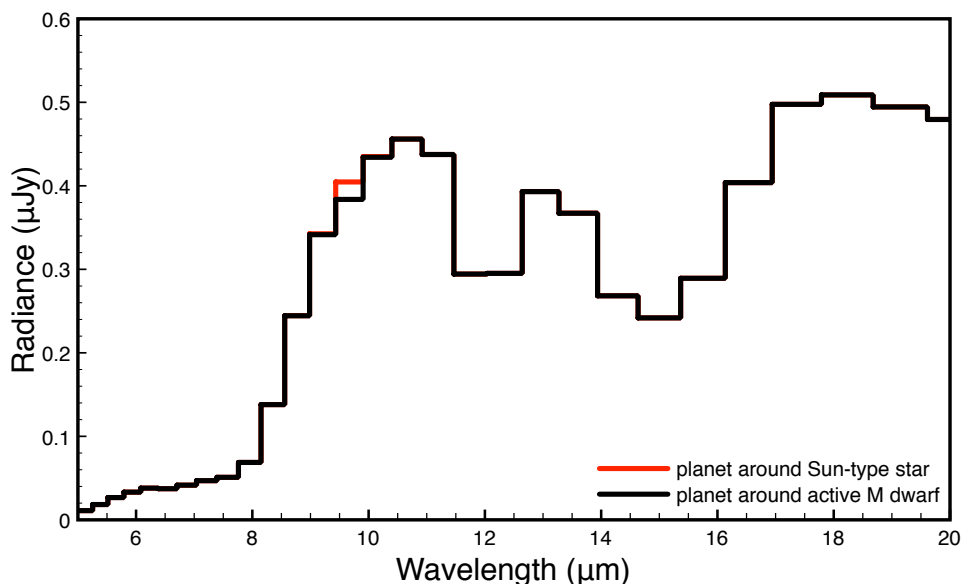


Figure 1. Model spectra of planets orbiting different stars. The black curve is the predicted reflection spectrum from a hypothetical planet orbiting AD Leo with about the resolution expected for *Terrestrial Planet Finder* missions. The red curve (see online version) shows the same, but with the planet orbiting the Sun. The difference, which is due to the abiotic build-up of O_3 , is at the limits of detectability. Different planetary conditions and stellar parameters may make this discrepancy larger.

for methyl-chloride (CH_3Cl) (Segura et al. 2005), or nitrous oxide (N_2O) (Sagan et al. 1993). In this section, we discuss how the stellar spectral energy distribution (SED) of M dwarfs can significantly impact our ability to identify biospheres.

Different SEDs profoundly affect atmospheric chemistry, as many reactions are the direct result of photolysis by UV photons, or indirectly the result of photolysis reactions that produce radicals that rapidly react with other species. Cool stars emit longer wavelength radiation, leading to a lower amount of energy in the UV region responsible for many photolytic reactions, and correspondingly slower photolysis rates. However, active M dwarfs such as AD Leonis (AD Leo) emit significant energy fluxes at wavelengths shortward of 200 nm, allowing a subset of photochemical reactions to proceed at a rate comparable to that around warmer stars. As a result, the photolysis reactions caused by these photons may proceed at Earth-like rates on planets around cool stars.

As an example we consider the effects of the SEDs of the Sun and AD Leo on a hypothetical planet orbiting in the HZ (see Segura et al. (2005)). The abundance of O_2 and O_3 in an atmosphere is a function of photolysis rates, and hence different SEDs could influence the abundance of these important biomarkers in a planetary atmosphere. On hypothetical planets around AD Leo, short-UV radiation from flares can lead to photolysis of O_2 , H_2O , and CO_2 , liberating O atoms. These O atoms can then react with O_2 to form O_3 . However, because O_3 photolysis occurs at longer wavelengths than O_2 photolysis, and these longer wavelengths are relatively scarce in all M dwarf SEDs, the destruction of the O_3 will be slower. *This could lead to build-up of atmospheric O_3 from processes that are photochemical and not biological.*

The net impact of the influence of SEDs on a planetary spectrum can be seen in Fig. 1. The black line shows results from a coupling of our photochemistry model (Pavlov et al. 2001) with our line-by-line spectral model (Crisp 1997). This particular simulation is of a spectrum from an organic-rich planet without biological O_2 production in the HZ of AD Leo. The red line represents our simulations of the same planet in the habitable zone of the Sun. The offset between these two lines results from AD Leo’s lack of emission of photons with wavelengths in the range 200–800 nm, which destroy O_3 . This result demonstrates how ignoring the stellar context of a planetary environment could lead to a false positive for life. The SEDs of M stars likely lead to biosignatures of their inhabited planets that are qualitatively different than those expected from inhabited planets orbiting F, G, and K stars.

4. Tidal Constraints on Habitability

Terrestrial planets orbiting close to their host stars may be deformed by the gradient of the gravitational force across their diameters. The tidal bulge raised on the planet will generally not be aligned with the line between the gravitational centers of the two bodies as long as 1) the orbit is eccentric ($e \neq 0$), or 2) the rotational period is different from its orbital period ($P_p^{\text{rot.}} \neq P_p^{\text{orb.}}$), or 3) the spin has an obliquity with respect to the orbital plane ($\psi_p \neq 0$). Although gravity tries to align the bulge, friction within the body resists, resulting in “tidal heating.” Conservation of energy and angular momentum forces the planet’s semi-major axis a , e , $P_p^{\text{rot.}}$, and ψ_p to steadily change.

Initially tides drive $\psi_p \rightarrow 0$ (“tilt erosion”), and $P_p^{\text{rot.}}$ evolves towards the “equilibrium rotation” $P_p^{\text{equ.}}$. When $\psi_0 \approx 0$, the planet will not experience seasons, i.e. over the course of an orbit, the insolation distribution on the planet will not vary. If $P_p^{\text{rot.}} = P_p^{\text{equ.}}$, one hemisphere of the planet will permanently be irradiated by the star, while the night side will freeze, which may prevent global habitability (Joshi 2003). Moreover, “tidal heating” in the planet may cause global volcanism or rapid resurfacing as observed in the Solar System on Io.

We define the “tilt erosion time” t_{ero} to be the time tides require to decrease an initial Earth-like obliquity of $\psi_p = 23.5^\circ$ to 5° , which depends on the initial a , e , and $P_p^{\text{rot.}}$. In the left panel of Fig. 2, t_{ero} is projected on to the a - e plane, as calculated with the tidal model of Leconte et al. (2010). The tidal time lag of the planet τ_p , the interval between the passage of the perturber and the tidal bulge, is scaled by $\tau_p = 638 \text{ s} \times Q_\oplus / Q_p$ to fit the Earth’s time lag τ_\oplus and dissipation value Q_\oplus (Neron de Surgy & Laskar 1997). $Q_p = 100$ and an initial rotation period $P_p^{\text{rot.}} = 1 \text{ d}$ are assumed. An error estimate for Q_p of a factor 2 is indicated with dashed lines. The test planet has one Earth-mass and orbits a $0.25 M_\odot$ star. The HZ of Barnes et al. (2008) is shaded in grey. Obviously, planets in the HZ experience $t_{\text{ero}} < 0.1 \text{ Gyr}$. For lower stellar masses, $t_{\text{ero}} \ll 0.1 \text{ Gyr}$ for terrestrial planets in the HZ (Heller et al. 2010). For terrestrial planets in highly eccentric orbits in the HZ, tilt erosion can occur within 10 Gyr for stellar masses as large as $1 M_\odot$.

The tidal equilibrium rotation period $P_p^{\text{equ.}}$ is a function of both e and ψ_p (Hut 1981). As an example, the right panel of Fig. 2 shows $P_p^{\text{equ.}}$ for the Super-Earth Gl 581 d projected onto the e - ψ_p plane. Observations (Mayor et al. 2009) provide $e = 0.38 \pm 0.09$ (grey line), while ψ_p is not known. At an age of $\gtrsim 2 \text{ Gyr}$ (Bonfils et al.

2005), an initial Earth-like obliquity of the planet is already eroded (Heller et al. 2010). For $\psi_p \lesssim 40^\circ$, then $P_p^{\text{rot.}} \approx P_p^{\text{orb.}}/2$.

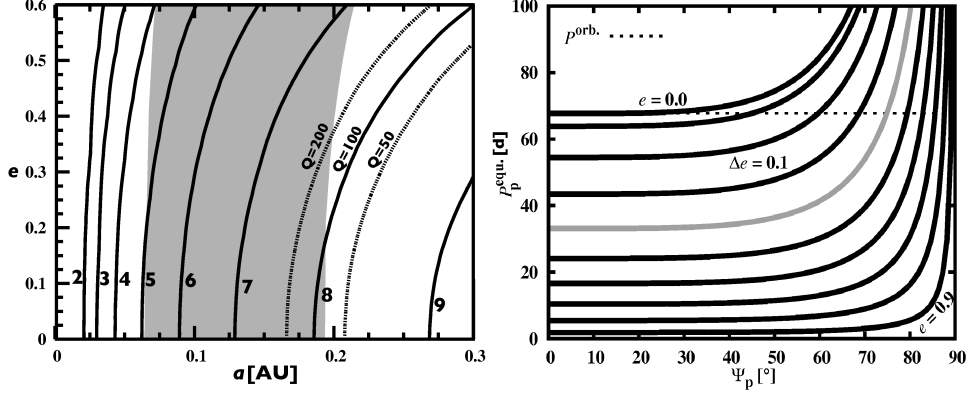


Figure 2. *Left:* Tilt erosion times in units of $\log(t_{\text{ero}}/\text{yr})$ for an Earth-mass planet orbiting a $0.25 M_\odot$ star. The HZ is shaded in grey. *Right:* Equilibrium rotation period of Gl 581 d as a function of obliquity ψ_p for different values of e . The observed $e = 0.38 \pm 0.09$ is close to the grey line for $e = 0.4$. The orbital period, 67 days, is marked with a dashed line.

“Orbital shrinking” ($a \rightarrow 0$) may pull an adequately irradiated planet out of the HZ (Barnes et al. 2008). Thus, planets observed outside the HZ might have been habitable once in the past or become habitable in the future. Similarly planets currently in the HZ may have been inhospitable earlier. Terrestrial planets in the HZ of stars with masses $\leq 0.25 M_\odot$ undergo significant tidal heating, potentially causing global volcanism (Jackson et al. 2008; Barnes et al. 2009; Heller et al. 2010), possibly rendering such planets uninhabitable. The consideration of tidal processes affects the concept of the habitable zone. Tilt erosion and equilibrium rotation need to be considered by atmospheric scientists, while orbital shrinking and tidal heating picture scenarios for geologists.

5. Evaporated/ing Cores of Gas Giants

Several hot Jupiters, e.g. HD 209458 b, show evidence of mass loss from their atmospheres (Vidal-Madjar et al. 2004). Many M dwarfs are far more active than the typical known planet-hosting stars. Hence, gas giants around these stars may also be losing significant mass. If these planets could be stripped of all their gas, a rocky/icy core could be left behind (Raymond et al. 2008). Furthermore, since *in situ* formation of large terrestrial planets (larger than Mars) appears challenging (Raymond et al. 2007), *detectable* rocky planets in the HZ of M stars may have followed just such an evolution. The core accretion model of planet formation (Pollack et al. 1996; Lissauer et al. 2009) posits that the cores of giant planets formed beyond the “snow line” (the region of a protoplanetary disk which is cold enough to permit the formation of water ice), and hence we may expect such cores to be volatile-rich. This section explores the possibility that terrestrial planets in the HZ of M dwarfs could be the remnant cores of ice or gas giants.

Atmospheric mass loss is most tightly coupled to the extreme ultraviolet flux, F_{XUV} , incident on a planet (Baraffe et al. 2004). On FGK stars, F_{XUV} drops over a timescale of Gyr (Ribas et al. 2005). For M dwarfs, stellar activity often produces XUV photons, but also decreases with time (West et al. 2008). Therefore, for a constant orbit, we expect the mass loss rate to decrease with time.

The complete removal of a gas giant’s atmosphere would likely leave behind a core with a mass of perhaps several M_{\oplus} (Baraffe et al. 2004; Raymond et al. 2008). On the other hand, some studies argue that the observations of HD 209458 b do not imply significant loss of mass (Ben-Jaffel 2007), and a theoretical study by Murray-Clay et al. (2009) suggested that complete evaporation of a gas giant’s atmosphere is unlikely. These competing hypotheses may now be testable. With the detection capabilities of the *Kepler* and *CoRoT* missions, rocky planets arising from a variety of histories may be detected.

In addition to mass loss, tides will play an important and interrelated role in the evolution of an evaporating gas or ice giant. Jackson et al. (2010) showed that the coupling of mass loss and orbital evolution may have played a significant role in CoRoT-7 b’s history. Several important feedbacks between mass loss and tidal evolution are possible. As a decreases, tides will accelerate orbital decay and mass loss. However, as mass decreases, orbits can decay more slowly. Orbital decay can occur on a timescale of Gyr, similar to the timescale for F_{XUV} for M dwarfs to diminish. Therefore, as tides pull a planet in, the mass loss increases due to proximity, but decreases due to less flux, but as mass is lost, tidal evolution slows.

Although Jackson et al. (2010) explored mass loss for CoRoT-7 b, the analogous problem for M dwarfs has yet to be tackled, in part because F_{XUV} is poorly constrained. In particular for M dwarfs, stellar activity does not evolve smoothly, as it is often punctuated by strong outbursts that may drive fast mass loss. Nonetheless, the example of CoRoT-7 b suggests that similar processes may be important for planets orbiting M dwarfs. As such planets are discovered, determination of their histories will be critical, as evaporated cores may not even be habitable.

6. Magnetic Shielding of Exo-Earths in the Habitable Zones of M Dwarfs

Many planets in the HZs of M dwarfs will be exposed to denser stellar winds and be tidally locked. As a consequence, the exoplanet community initially reached the consensus that the slow rotation of the planets will prevent the development of magnetic fields strong enough to shield surface life. In this section, we show that a planet in the HZ of an M dwarf, even if rotating very slowly, can have stronger magnetic shielding than previously thought.

Although planets in the HZs of M dwarfs do not necessarily rotate synchronously due to tides (see § 4, Correia et al. (2008) or Barnes et al. (2010)), tidal locking still leads to slow rotation, except for the very latest M dwarfs and/or large eccentricities. Planetary scientists have been working for decades on models to reproduce the magnetic moments M of planets and satellites in our Solar System. The best model generated to date, in the sense of reproducing the measured magnetic moments of most objects in the Solar System, is by Olson & Christensen (2006).

We applied that model to the case of hypothetical exo-Earths (with masses up to $12 M_{\oplus}$), to determine the strengths of their magnetic fields. We assume their interiors are stratified in two separate layers, a mantle and a core. We also assume that the planets

have thin atmosphere and ocean/crust layers which account only for 1% of the planetary radius. We use two different chemical compositions for each layer: a pure iron core and an iron alloy core, containing 10 mole % S, and for the mantle we use pure olivine and perovskite+ferropericlasite compositions, which resemble, respectively, the upper and lower mantle compositions of the Earth.

We implemented all possible combinations of those model layers into the standard equations of planetary structure to obtain the density profile of the planets and from those density profiles computed the parameters needed to determine their magnetic moment, i.e. the radius of the core, the average bulk density of the convective zone, and its thickness.

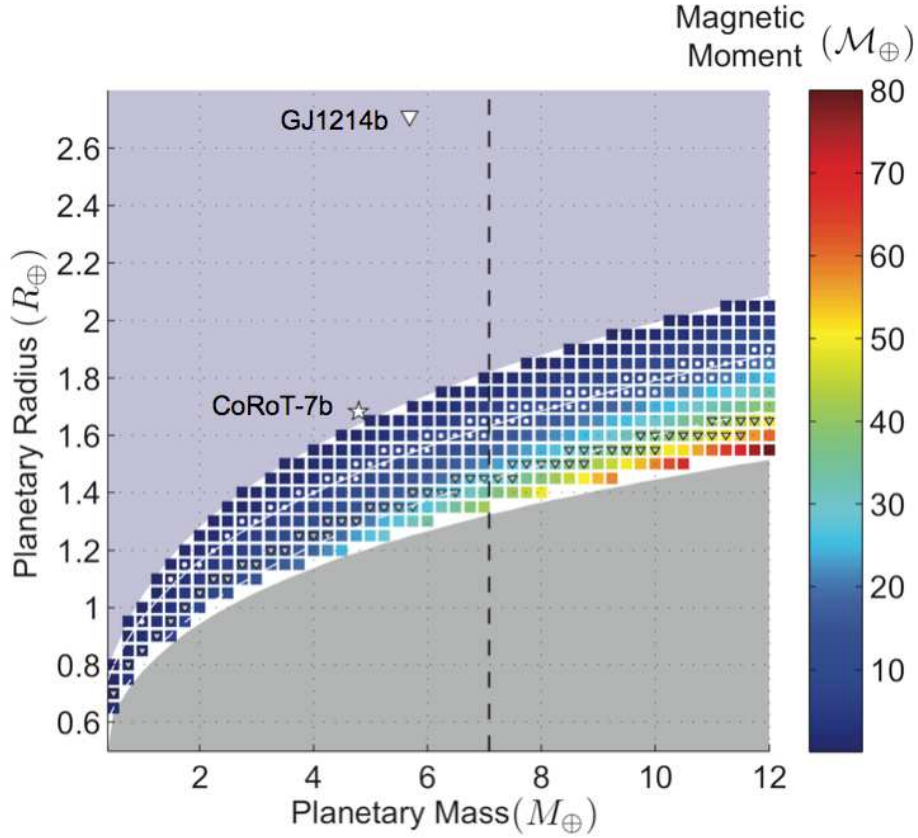


Figure 3. Magnetic moment model estimates for planets with masses up to $12 M_{\oplus}$, a pure iron core, and perovskite+ferropericlasite mantle compositions. The color scale (see online version) on the right corresponds to magnetic moment values between 0 and 80 times that of the Earth. The region below the colored points corresponds to planets made out of core materials denser than iron, while the region above corresponds to planets with radii too large, and therefore too low density, to have a core capable of generating a magnetic field. The triangle in the upper edge of the plot corresponds to GJ 1214 b, and the star symbol corresponds to CoRoT-7 b (Léger et al. 2009). For the core and mantle compositions in these models, neither of those two planets will have a magnetic field, but this result can change in the case of CoRoT-7 b for slightly different interior chemical compositions.

The magnitude of the magnetic moment of a planet varies with density and core-mantle composition. Pure iron core and perovskite+ferropericlasite mantle models result in the smallest planetary core radius and therefore the smallest moment, but even in this case the value for Earth-sized planets like those in our simulations will still be at least $0.4M_{\oplus}$, independent of the planets' rotation rates. All other models produce stronger dipoles. Fig. 3 summarizes our findings for a grid of simulated planetary mass and radius values of exo-Earths with masses up to $12 M_{\oplus}$, assuming the mantle and core compositions that gave the weakest magnetic moment, as described above. Therefore, the values in the figure are lower limits to the expected magnetic moment strengths.

Planets with larger masses and smaller radii are more likely to have larger dipole moments and stronger magnetic fields at the surface, because denser planets tend to have larger cores. The main conclusions are: 1) *the magnetic moment of a planet does not depend on its rotation rate*; 2) the magnetic moment depends instead on its mass and size, its chemical composition, and the efficiency of convection in its interior; and 3) any terrestrial planet up to a few Earth masses in the HZ of an M-dwarf might have a strong enough magnetic field to shield its atmosphere and surface.

Notice, however, that these models do not account for changes in the thickness of the convective zone or the convective flux. Also, planets under extreme conditions, i.e. highly inhomogeneous heating or very strong stellar winds, will undoubtedly have their magnetic fields affected.

7. Revisiting the Habitable Zone: Summary of the NAI Workshop Discussions

To take stock of the current state of the field of planetary habitability, the NASA Astrobiology Institute's Habitability and Biosignatures Focus group organized a workshop in Seattle, WA on Aug 3–5, 2010. This workshop gathered together 38 scientists from the fields of biology, geology, atmospheric science, ecology and astronomy. The primary goal of the workshop was to identify, review and prioritize planetary and stellar characteristics that affect habitability, and to provide an interdisciplinary synthesis of these developments in our understanding of planetary habitability. As a secondary goal, the workshop initiated a discussion on the development of a multi-parameter means of assessing the likelihood of extrasolar planet habitability. In this section we will briefly describe workshop highlights in the major topic areas covered. The full report will be available in 2011 (Meadows et al., in prep.).

Life's Requirements: The recently-published NRC report on "The Limits of Organic Life in Planetary Systems"¹ finds that life requires a scaffolding element which can form covalent bonds with other elements that are relatively easily broken. Weaker, non-covalent electrostatic bonds are also crucial, as they are required to maintain the 3-D structure of proteins. As life's molecules require both covalent and non-covalent bonds to function, this strongly favors a polar solvent like water, and much of our discussion in this session was on scientific arguments for water as the most likely solvent for life. Energy is also required, but in the HZ of Kasting et al. (1993), stellar photons provide an essentially limitless supply. More speculatively, the boundaries of an HZ may be a function of the metabolic pathways utilized on a particular planet.

¹http://www.nap.edu/catalog.php?record_id=11919

Stellar Radiative Effects: The star drives a planet’s climate, but can also negatively impact habitability by subjecting the planet to high-energy radiation and particles. Modeling work on the effect of flares on Earth-like planets orbiting in the HZ of M dwarfs find that this latter effect may be mitigated if the planet has an existing ozone layer, and if flares are infrequent (Segura et al. 2010). UV radiation from the flare has little effect on O₃, and it is the chemistry associated with the proton flux from the flare that produces the most damage. However, DNA-damaging UVB flux reaching the surface at the peak of the flare was only 1.2 times Earth’s level.

Planetary System Architecture: Discussion in this session emphasized the importance of planetary rotation rate, obliquity and eccentricity, characteristics that are often extremely difficult to constrain observationally. Tidal locking with synchronous rotation can also lead to a 0 or 180 degree obliquity (planetary pole perpendicular to the orbital plane) such that the planet’s poles do not experience seasonal melting, see § 3. This state can lead to runaway glaciation as the poles freeze and planetary albedo steadily increases. High obliquity and moderate eccentricity can push out the outer edge of the HZ (Spiegel et al. 2010). Tidal heating can also be so strong as to render a planet in the HZ uninhabitable (Jackson et al. 2008; Barnes et al. 2009).

Forming Habitable Planets: Highlights of this session included a discussion of water and carbon worlds. Radioactive heating from supernova-sourced ²⁶Al can deplete water in planetesimals, leading to drier planets. Without ²⁶Al, Earth might have formed with 30–50 times as much water resulting in oceans 400 km deep. This “waterworld” might be uninhabitable however, as the overlying pressure could form an ice layer on the ocean floor, cutting off nutrient communication with the rocky interior. Planet formation and disk-chemistry modeling suggests that 1 in 3 planetary systems has a C/O ratio higher than about 0.8 and may form SiC as the principle planetary constituent Bond et al. (2010).

Planetary Characteristics: This session included an in depth discussion of planetary tectonic regimes. Internal energy is needed to drive convection for plates of a particular strength and planets may go through different tectonic regimes, including plate tectonics as we know it, but also episodic overturns and stagnant lid regimes. Even the Earth is likely to only have had smooth plate tectonics for the last billion years (Condie 1998). This could have ramifications for the carbonate-silicate cycle which may have buffered the Earth’s climate for the past 4 Gyr (Walker et al. 1981). A Dune-like world, with only 1–10% of the Earth’s water abundance, could both cool more efficiently at the inner HZ edge, and avoid an ice-albedo feedback at the outer edge, and hence may have a much broader HZ than predicted by Kasting et al. (1993).

Detecting Habitability: This session included discussions of detecting distant oceans. Robinson et al. (2010) have used a realistic 3-D spectral model of the Earth to show that photometric observations at specific extrasolar planetary phases could be used to discriminate between planets with and without significant bodies of liquid on their surfaces. Polarization signals also permit the detection of surface liquids, and the peak in polarization percentage may give clues to atmospheric thickness.

8. Conclusions

Less than one month after the Cool Stars XVI meeting, Vogt et al. (2010) reported the RV detection of a potentially rocky planet ($m_p \geq 3M_\oplus$) orbiting in the HZ of the M3 star Gl 581 in a nearly circular orbit. If confirmed, this planet is the first discovered

near the middle of the HZ of a main sequence star, and, as expected, that star is an M dwarf. So how does this planet measure up in terms of potential habitability? Vogt et al. note that the host star is extremely quiescent, to the point that they cannot really detect any jitter, and hence stellar activity is not currently an issue for the planet. However, the star is at least a few Gyr old (Bonfils et al. 2005), hence we cannot exclude the possibility that fatal harm was done to a potential biosphere in the past. The planet is tidally locked, or in a spin-orbit resonance (Heller et al. 2010), but we do not know its rotation rate. The planet's mass is large enough that it can sustain tectonic activity for 10 Gyr, assuming it formed with a similar ratio of radiogenic isotopes as the Earth (tidal heating is minimal, even for $e = 0.2$). Therefore, from the RV data, we can not discern any major issue impeding habitability. Unfortunately, though, remote detection of its biosphere is not possible for the foreseeable future, as at 0.15 AU from its host star, reflection spectra will be unavailable from any currently planned space mission.

In spite of early skepticism, planets orbiting M dwarfs can be inhabited. Although many issues have been identified, such as tidal locking and atmospheric removal, more careful modeling has shown that these phenomena are not so deadly. While improvements in our knowledge via modeling will continue, transmission spectra of planets transiting M dwarfs will provide, at least for the next decade, our only observational means to directly assess the habitability of planets orbiting cool stars.

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